Integration and Control of Morphing Wing Structures for Efficiency/Performance

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Investigator(s): Corey Ippolito (PI), NASA Ames Research Center; Ron Barrett-Gonzalez (Co-PI), Zaki H. Abu Ghazaleh, University of Kansas; Jason Lohn (Co-PI), Carnegie Mellon University; Vishesh Gupta, Jake Salzman, Dylan King (Student Interns), NASA Ames Research Center

Purpose

The purpose of this project is to investigate distributed wing-shape morphing flight control for increased fuel efficiency and performance. The investigation focuses on (1) flight control through distributed morphing of wing geometry to improve performance, efficiency, and safety while reducing drag and fuel burn; and (2) investigating and advancing the maturity of pressure adaptive honeycomb technology as a mechanism to achieve wing shape morphing. This project proposes a vehicle configuration concept that features a multi-functional shape morphing wing structure as an alternative to standard vehicle configurations that utilize control surface actuators for flight control.

In the Phase 1 effort we limit our study to roll control through asymmetric wing-camber shape changes in comparison to ailerons in terms of lift-to-drag efficiency and control authority. We designed and manufactured full-scale prototypes of a Pressure Adaptive Honeycomb (PAH) actuator for a large unmanned aircraft platform. The results demonstrate that a PAH actuator system is scalable, with the prototype able to withstand full aerodynamic loading under landing conditions with a safety factor of 2.5, and results suggesting a significant weight savings over a conventional hydraulic flap system. In addition, we developed a second flight-ready small-scale prototype for lateral mode roll control analysis; we show the actuator provides sufficient roll control authority for a scaled unmanned aircraft platform with up to 47% improvement of L/D efficiency in maneuvering at lower speeds and 29% improvement across the entire speed regime. We outline an architecture for a distributed morphing wing flight control system. Finally, we develop the mathematical models and simulation tools necessary for evaluating the concept, developing a custom simulation environment that combines non-linear 6-DOF flight dynamics with variable geometry vortex-panel, and accelerated on COTS GPU's (graphics processing units) for real-time simulation evaluation of the distributed morphing-wing concept. This initial investigation lays the ground work for continued investigations into flight control for wing-morphing and related novel actuation concepts.

Background

The prevailing paradigm for flight control actuation of a fixed wing aircraft involves deflection of small control surface actuators affixed to a geometrically static lifting body; the classical approach yields simple mechanisms, stable flight characteristics that are sufficiently described by low-order time-invariant models, and simplicity in control analysis and design (e.g., amendable to classical theory, allows single objective linear time-invariant controller design, and facilitates design for safety and margins). However, numerous studies show that a multifunctional wing-shape morphing mechanism for flight optimization and control would provide substantial improvements across nearly all flight conditions, including increased aerodynamic efficiency, drag reduction and enhanced lift-to-drag performance, enhanced maneuverability, reduced fuel consumption, increased actuator effectiveness, decreased actuator power requirements, increased control robustness, control redundancy, shorter required takeoff/landing length, flutter and stall mitigation, reduced airframe noise, increased stability and reduced stall susceptibility. There is a substantial body of research related to shape morphing aircraft, though despite the significant potential and over 17 years of flight heritage, no adaptive wing technology has been approved by the FAA or used in commercial aviation. Several challenges have been identified in recent literature, including:

materials used for morphing are typically difficult to certify for flight; many promising small-scale laboratory concepts do not function well at vehicle scale; it is difficult to design an effective feedback control architecture that controls distributed wing camber shape actuation; it is difficult to estimate and sense flow state around a vehicle necessary for wing shape optimization in an accurate, complete, and timely manner; and it is difficult to determine optimal strategies to achieve multiple simultaneous objectives involving maneuvering, stability, robustness, and aerodynamic efficiency while ensuring satisfaction of control constraints. Many control challenges are introduced by the difficultly in generating manageable models that sufficiently capture fluid flow interaction about variable geometry with the dynamic response of the flight vehicle. A limited amount of research addresses systemic impacts of morphing as the primary vehicle flight control system.

Recently, researchers at the University of Kansas have developed a technology called Pressure Adaptive Honeycomb (PAH) for adaptive aircraft structures based on pressurization of aircraft grade honeycomb material. Early studies and scale prototypes have demonstrated many potential benefits of PAH for wing morphing actuation. PAH is constructed completely with FAR/CS25 materials. PAH structures can achieve large gross structural deformations quickly. PAH show favorable performance compared to alternative techniques. PAH generates much higher strains than any conventional adaptive material, such as shape memory alloys (SMAs) or piezoelectric materials. PAH delivers a work energy density an order of magnitude greater than SMAs, conventional hydraulics or electromechanical actuators. PAH honeycomb can be installed selectively to provide a wide variability of local morphing actuation possibilities. The PAH concept can scale to larger sizes without issue.

This project builds on the existing literature, advancing the maturity of a promising morphing wing actuation, investigating system level impact of a distributed morphing wing control system concept, and investigating multiobjective control system strategies that achieve maneuvering objectives for flight control while optimizing efficiency at any given flight condition.

This project aligns with the FY11 Seedling Fund call addressing game-changing flight vehicle concepts, and further presents a control system methodology that supports light-weight multifunctional adaptive structures, leading toward elimination of control surface actuation subsystems from next generation vehicle designs. The research is aligned with NASA ARMD's goals of decreased fuel burn, decreased noise emissions, shorter field lengths, and decreased drag. This project ties directly into NASA programs investigating drag reduction, structural aeroelastic control, lightweight materials, and adaptive and flexible wing structures. Successful completion of this project advances the TRL of a promising actuation technology, delivers new models and methods for analyzing a morphing geometry concept, demonstrates application of advanced nonlinear control techniques to next generation aircraft systems which can be applied to other emerging problems in the field (e.g., multi-objective, nonlinear, high dimension, large coupled systems), and provides quantitative analysis of performance and efficiency achieved by the morphing wing vehicle configuration concepts.

Approach

This Phase 1 project has three primary objectives. The first objective is to demonstrate scalability and performance of a full-scale PAWS (Pressure Adaptive Wing System) by designing, developing, and analyzing a large-scale prototype. The scale must be relevant to manned flight on a real flight vehicle platform, with a design study, prototype, and evaluation to be delivered at the end of Phase 1. The second objective is to demonstrate the effectiveness and benefits of wing-morphing as a primary actuator within the limits of a Phase 1 effort. Since the full-scale PAH/PAWS prototype would not be completed until the end of Phase 1, a parallel effort was initiated at NASA Ames to quickly construct a small prototype wing-morphing system that could be used for this analysis. We developed a small-scale prototype on a NASA UAV platform (one-quarter scaled Cessna 182 model), analyzing and developing control laws to show the effectiveness and efficiency of a camber-shape morphing concept for conducting roll maneuvers. The team received approval to flight-test the prototype actuator on the quarter-scale UAV, should flight testing be pursued in follow-on research. The third objective of this project is to develop a full flight control system architecture using distributed wing morphing actuation, and develop the tools required to analyzing and simulating the concept on a flight vehicle over the entire flight regime. There are significant challenges to modeling and simulation of a morphing-wing aircraft, and no high-fidelity tool exists to the knowledge of the authors. In the canonical derivation of fixed-wing flight dynamics, static geometry is a necessary and fundamental assumption that allows low-order linear representations to sufficiently reflect the response of the flight vehicle for control system analysis and synthesis; linearization occurs around stable stationary points that allows for a relatively small number of stationary points to capture the full range of the vehicle's response, resulting in the standard aerodynamic coefficient derivative model. Introduction of non-static geometry on a large enough scale that it alters homogeneous system response invalidates this approach, as control input changes the model's characteristic response, making it difficult to identify a separate the control effect on a stationary plant, and using traditional approaches would require linearization around an unfeasibly large number of points. To support our study, we derive a new mathematical formulation for a morphing geometry flight vehicle and the actuation mechanism which will support future analysis, simulation and control synthesis.

The following tasks were performed under this Phase 1 effort: (1) Conduct a background literature survey on wing morphing; (2) Perform a system design study and design optimization for a full-scale PAH/PAWS prototype; (3) Manufacture and deliver a full-scale PAH/PAWS prototype (for delivery at the end of Phase 1); (3) Develop a small prototype wing-morphing actuator for a small-scale UAV for use in the Phase 1 analysis; (4) Analyze and model the prototype system's performance; (5) Develop optimal control laws for roll-maneuvers through asymmetric camber morphing on the left and right wings; (6) Assess the scaled-prototype performance, determining control effectiveness/authority and L/D efficiency in executing roll maneuvers compared to the baseline quarter-scale vehicle with traditional aileron-control; (7) develop the concept for a full flight control architecture with distribute wing-morphing of a transport-class aircraft, and (8) develop models and simulation tools that allow evaluation of the full 3D non-linear flight control architecture, implementing a simulation test-bed that combines full non-linear 6-DOF rigid-body dynamics with 3-D vortex-panel evaluations at run-time that supports arbitrary aircraft-shape morphing geometries and runs in real-time (uses many-core parallelizing accelerations through a graphics processing unit).

Summary of Research

<u>Background Literature Survey</u>. A general background survey for wing morphing was published (Gupta and Ippolito, 2012) with a detailed survey in the appendix of (Barrett, 2013) and in the background section of (Ippolito, 2013).

<u>Design and Manufacture the Full-Scale PAH/PAWS Prototype</u>. Given tremendous variability in the design of a PAHS structure and limited time and resources, the team decided to adopt a 'build it/analyze it/suggest refinements' approach. It was determined that a second small-scale prototype would needed for the NASA effort, while the KU team would focus largely on manufacturing the full-scale PAWS prototype for Phase 1. Based on initial design meetings, the preliminary specifications and requirements for the PAWS prototype were determined. The target aircraft - the NASA Swift UAS - is a 42 foot wing-span flying-wing glider, for which an airfoil with low pitching moment coefficients and high cruising efficiency is favorable. The PAWS prototype replaces a section of the wing shown in Figure 1, with 50cm semi-span and 1.09m chord.

The Phase 1 budget was not sufficient to conduct an intensive airfoil design and optimization study. The team decided to identify a representative 'target' airfoil shape, with the airfoil transitioning from the baseline Swift airfoil shape to a target high-lift shape during takeoff and landing. A search of existing airfoils shapes was conducted to identify candidate shapes, which allowed the PAWS prototype be constructed and completed by the end of Phase 1.

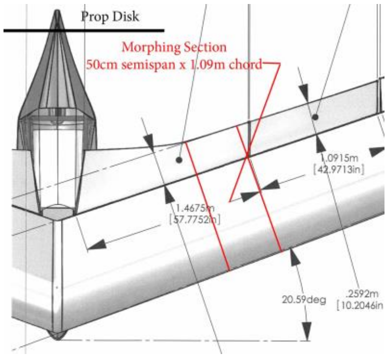

Figure 1. Swift UAS and Prototype Wing Morphing Section

Details of the analysis are provided in (Barrett-Gonzalez, 2013). The Swift UAS baseline airfoil has a unique shape, and analysis in XFOIL shows desirable characteristics as shown in Figure 2; good L/D performance, and relatively low, constant pitching moment (Cm) relative to attack angle, though the lift curve does show an abrupt stall at high alpha. The Selig 1210 was selected as a representative target airfoil shape that the morphing wing would need to achieve, with the goal of morphing from the current Swift airfoil in cruise to a Selig 1210 during take-off and landing.

The Selig 1210 shows greater efficiency at low attack angles, is geometrically similar to the Swift airfoil (see Figure 3), offers higher L/D performance at low attack angles, and does not show the abrupt stall characteristic of the Swift airfoil. Morphing between the two sections allows the L/D values in cruise to top 140, but also maintain CLmax values of up to 2.2 - nearly 50% higher than the unmorphed airfoil.

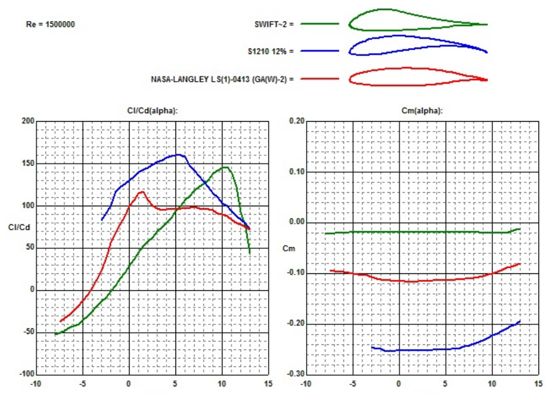

Figure 2. Swift UAS airfoil versus Selig 1210 and NASA Langley LS(1)-0413

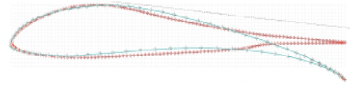

Figure 3. Comparison of Selig 2013 with Swift

The design schematic for the PAWS morphing actuator is shown in Figure 4.

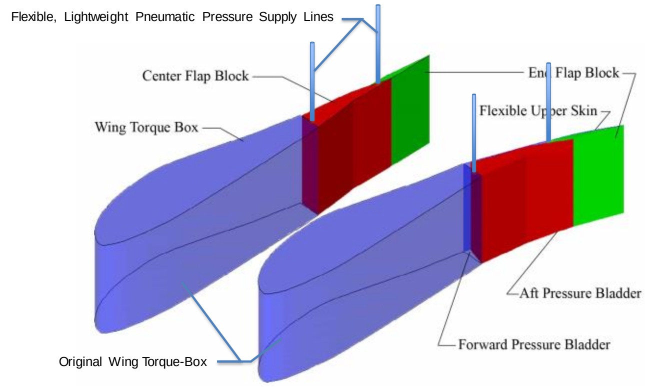

Figure 4. PAWS Prototype Design Schematic.

PAWS Design Optimization. Morphing the Swift UAS wing from the original profile to a Selig 1223 requires a nontrivial amount of manipulation. To accomplish this task, a series of computer simulations were run comparing several thousand actuator cell and block configurations (illustrated in Figure 5). The code was set to compare complexity of cell structures, number of cell structures, number of fixed blocks and rotation points. The goal was to minimize the articulations while maintaining the highest level of dimensional fidelity, with a local geometric parameter not exceeding 5% of the local dimension.

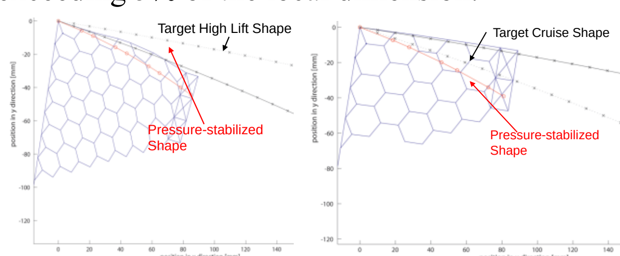

Figure 5. Honeycomb Geometric Deformation

In an effort to compare airfoil complexity and weight increment against the performance increments, four airfoil sections are compared. The first is the baseline Swift airfoil. The second section is a single-hinge 30% pressure-morphing airfoil with hinge at 20 deg. The third is a double-hinged section with 20 deg. per articulation. The fourth and final section is a triple-hinged section with 20 deg per articulation. Figure 8 shows the lift increments and C_{lmax} values predicted for each of these sections.

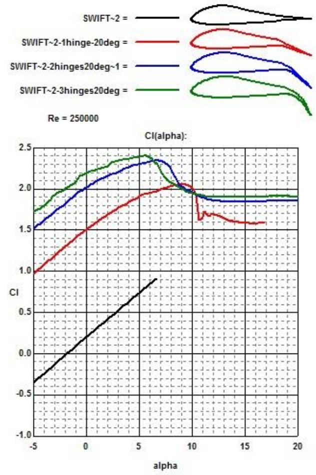

Figure 6. Aerodynamic Performance of Single, Double and Triple-Hinged Pressure Adaptive Airfoil Sections

PAWS Prototype Construction. Several PAWS prototype wing sections were fabricated. The initial test articles shown in Figure 7 were generated to check articulation levels, skin deflection, stiction, friction and slop associated with such articulation. The single, double, and triple-section test articles outfitted with adaptive honeycomb structure and pressure bladders for articulation are shown in Figure 8, along with their maximum deformation. Test articles were designed to withstand full aerodynamic loading under landing conditions with a safety factor of 2.5. The weight of the manifold actuator systems and hinges are: 0.85lb, 1.59lb and 2.38lb for single, double and triple-hinge systems. If one extrapolates this to a flap system akin to that used on a typical irreversibly controlled general aviation aircraft, the system-level weight savings will be in excess of 85%. For details, see the attached project report (Barrett-Gonzalez, 2013).

Figure 7. Morphing Wing Section Prototype, Two Flap Blocks and Two Articulations, 110cm Chord x 25cm Semispan

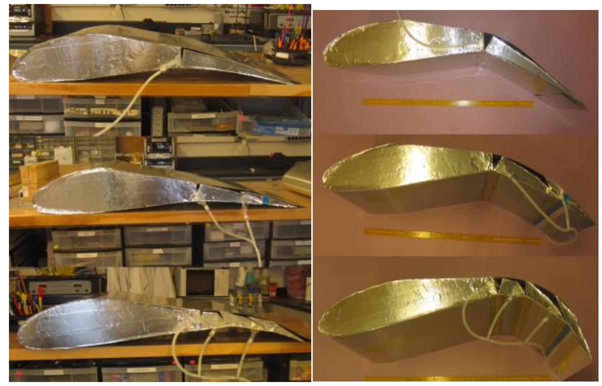

Figure 8. Single, Double, Triple-Sections, 1.1m Chord x 50cm Semispan

Small Scale UAV Morphing Wing Prototype Construction. A prototype actuator was needed to analyze control effectiveness, so a parallel effort was undertaken at NASA Ames to quickly construct a small-scale morphing wing that could be quickly and cheaply constructed for analysis and possibly flight tested. The Exploration Aerial Vehicle (EAV), a quarter-scale Cessna 182 unmanned aircraft with a NACA 2412 airfoil cross-section, was selected. Analysis was performed at a cruising condition of 400ft AGL at 20.5 m/s (40 knots) and 5 degree attack angle. For mechanical installation, the wing skin was replaced with a flexible neoprene skin covering, and six individually-addressable servomotors were mounted in the wing that could change the airfoil cross-sectional shape. The schematic of the actuator configuration is shown in Figure 10, along with an example resulting shape that could result. This configuration provides six control points per wing. Note that the number of motors, location, and actuation geometry was based solely on convenience for the installation. Optimization is beyond the budget of this project, though optimizing the placement of the motors, geometry of attachment, and number of motors would provide additional efficiency/performance improvements. The team received approval to flight test the prototype from the Airfield Airworthiness and Flight Safety Review Board (AFSRB) at Moffett Airfield, making flight testing of this aircraft being a possible follow-on task.

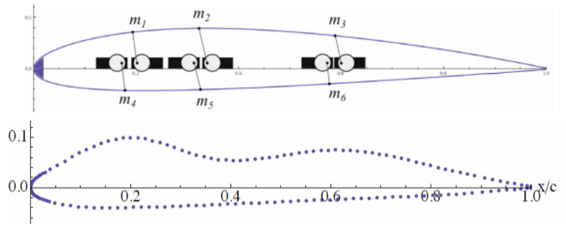

Figure 9. Small-scale Morphing Prototype Configuration and Example Wing Shape

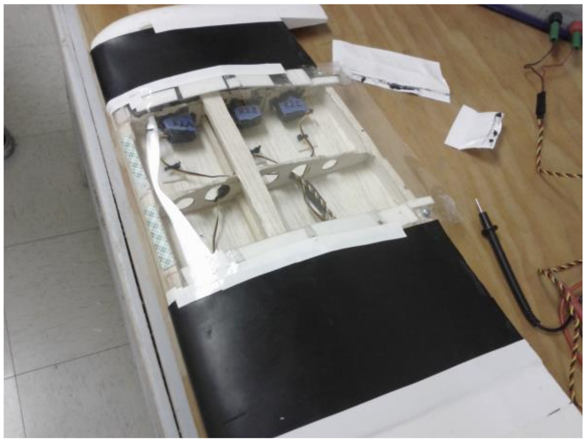

Figure 10. Small-scale Prototype Installation in the EAV Aircraft Wing.

<u>Prototype Analysis (Gupta and Ippolito, 2012).</u> An actuator model was created to generate 2D airfoil shapes from a given set of actuator positions, and the flexible skin was approximated using a spline function. Based on observation of the mechanical prototype, maximum/minimum deflection constraints were enforced on the top and bottom surface actuator positions, as was relative position constraints between adjacent servos (no more than 2% chord change between adjacent servos). A database of 10E6 possible geometries were evaluated. The database was processed to determine optimized geometries for control. The optimization function mapped the appropriate input u=(m1,..,m6) to find the maximal L/D efficiency that resulted in a desired rolling and pitching moment. The CL/CM space was coarsely discretized into 100x100 buckets from CL=(0.4,1.15) to CM=(-0.15,0.06), with optimization performed over each point. The resulting efficiency map from CL/CM to L/D is shown in Figure 11.

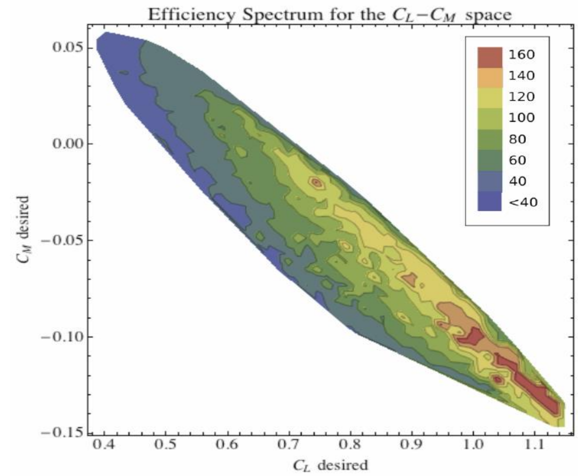

Figure 11. Efficiency Map

Flight control is accomplished utilizing asymmetric wing shape morphing to achieve desired roll/pitch moments with optimal L/D efficiency. The effect on the dynamics were modeled as

$$\dot{x} = Ax + Bu + C(u_m)$$

where $x = [v, p, r, \phi, u, w, q, \theta]$, $u \in \mathbb{R}^4$ includes the traditional aileron, elevator, rudder, and throttle control, $u_m \in \mathbb{R}^6$ represents the wing morphing actuator input applied asymmetrically to both wings, and $C: \mathbb{R}^6 \to \mathbb{R}^8$ maps the effect of wing morphing on the flight dynamics. The C mapping is given by

$$C = \begin{pmatrix} q_\infty S \sin(\beta)\left(-\cos(\alpha)\left(C_{D_L} + C_{D_R}\right) + \sin(\alpha)\left(C_{L_L} + C_{L_R}\right)\right) \\ d q_\infty S \left(\sin(\alpha)\left(C_{D_L} - C_{D_R}\right) + \cos(\alpha)\left(C_{L_L} - C_{L_R}\right)\right) \\ d q_\infty S \cos(\beta)\left(\cos(\alpha)\left(-C_{D_L} + C_{D_R}\right) + \sin(\alpha)\left(C_{L_L} - C_{L_R}\right)\right) \\ 0 \\ q_\infty S \cos(\beta)\left(-\cos(\alpha)\left(C_{D_L} + C_{D_R}\right) + \sin(\alpha)\left(C_{L_L} + C_{L_R}\right)\right) \\ -q_\infty S \left(\sin(\alpha)\left(C_{D_L} + C_{D_R}\right) + \cos(\alpha)\left(C_{L_L} + C_{L_R}\right)\right) \\ \frac{1}{2} c q_\infty S \left(C_{M_L} + C_{M_R}\right) \\ 0 \end{pmatrix}$$

The frequency/speed of actuation control in terms total forces/moments satisfied actuator requirements for primary flight control. The baseline ailerons were capable of generating faster and stronger control forces/moments than the asymmetric wing morphing prototype, though at the cost of efficiency and higher drag throughout the regime. Figure 12 shows a comparison between the ailerons and morphing wing system. The flight control using the shape-morphing prototype was able to achieve greater than 47% L/D efficiency improvements at low speeds, and at least 29.5% L/D improvement across the speed regime.

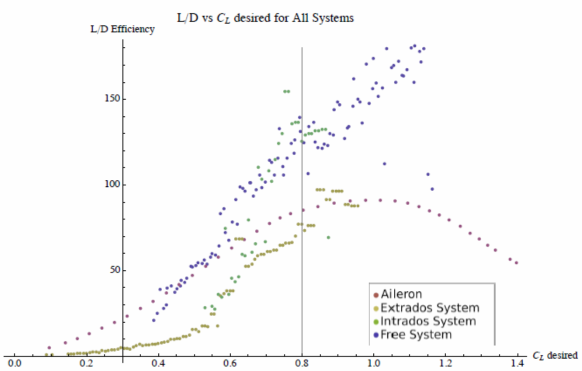

Figure 12. L/D Profile Comparison, Shape-Morphing versus Ailerons

To evaluate flight control, a feed-forward/feed-back control strategy was devised that controls roll angle using asymmetric wing shape morphing that achieves optimal L/D efficiency. Since this study focused on rolling-maneuvers only, the database search was limited to find most optimally efficient control inputs that achieved a desired differential lift (applied asymmetrically on the left and right wing) while being neutral in terms of differential pitching moment, so that the resulting shapes produce an optimal pure-rolling moment on the aircraft. The resulting solutions were placed in a lookup table for fast constant-time evaluation in the control law. The control architecture is shown in Figure 13. The controller first passes the desired roll angle through a command filter that computes the amount of differential lift needed to track the command signal in the feed-forward path. A feedback proportional-integral control law corrects tracking error and disturbances around the optimal performance point, adjusting the desired delta-lift signal to correct for observed tracking error. The aggregate delta-lift command signal is fed through the table lookup to determine the optimally efficient shape to achieve.

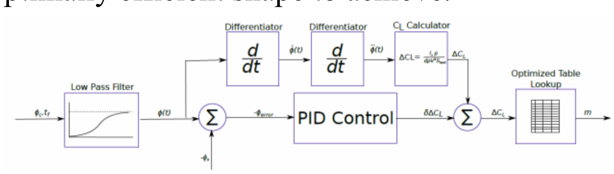

Figure 13. Control Architecture for Roll Control

The controller was tested in simulation against the longitudinal model of the UAV. The results from the study were published in (Gupta and Ippolito, 2012), which received the award for best student paper at the AIAA 2012 Aerospace@Infotech conference, and subsequently received a finalist award in the 2012 Intel science talent search competition.

Distributed Morphing Wing Control Architecture: In the attached report, the DMoWCS controller architecture is described (section 5.0). The control structure (shown in Figure 3 below) is composed of three major components: the pseudo-optimal trajectory optimization engine, a set of decentralized local feedback controllers, and a distributed sensor observer and state estimator. We have constructed a proposed formulation for the optimal trajectory generation methodology, as presented in the attached report.

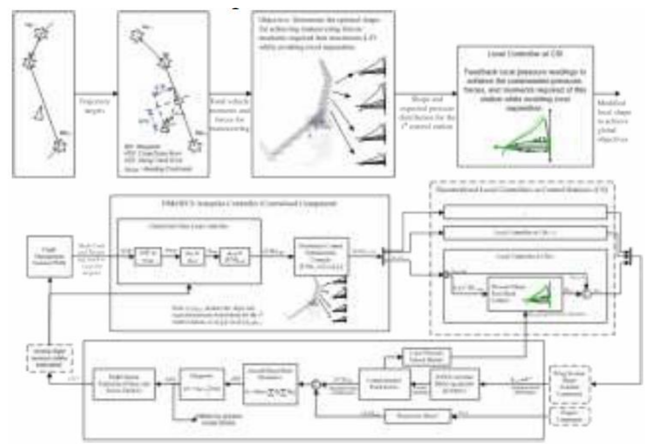

Figure 3. DMoWCS Control Structure

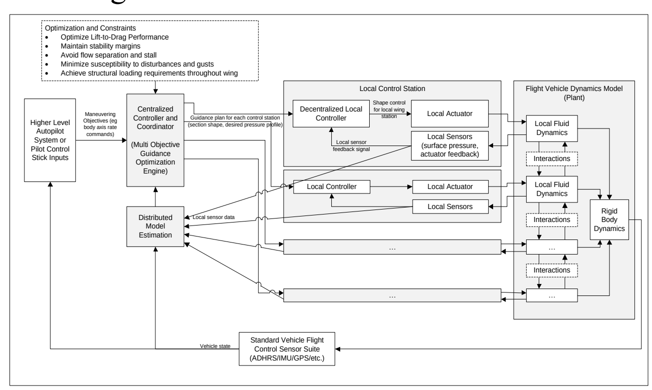

Figure 14. Control Architecture and Approach

The simulation architecture is shown in Figure 15 below.

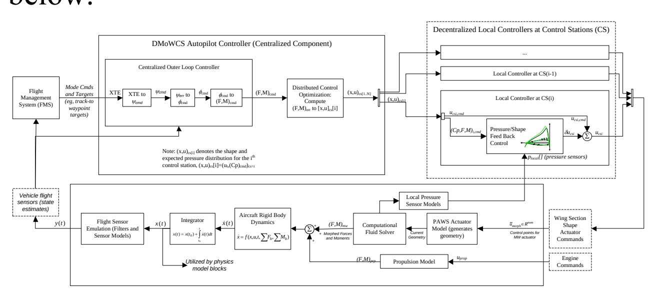

Figure 15. Control and Simulation Architecture

<u>Modeling and Simulation of a Distributed Morphing Wing Vehicle System</u>: The goal of this project is to evaluate the morphing concept when distributed to multiple control stations across the wing. Unfortunately, there are many challenges associated with the modeling and simulation of such a system, as traditional techniques for flight simulation are insufficient when arbitrary distributed wing-shape deformations are applied as control inputs to a vehicle in flight. The final accomplishment from this phase 1 was to create a simulation environment that incorporates real-time vortex-panel code into a rigid-body 6-DOF simulation environment.

A vortex-panel model of the target aircraft was created that ties 2D shapes together to estimate a 3D model. 2D slices from the geometric model were extracted to generate the input model (see Figure 8). The vortex-panel output is fed into a standard 6-DOF nonlinear kinematics model. The simulation was implemented in the Reflection Architecture, which interfaces into hardware in the loop simulation.

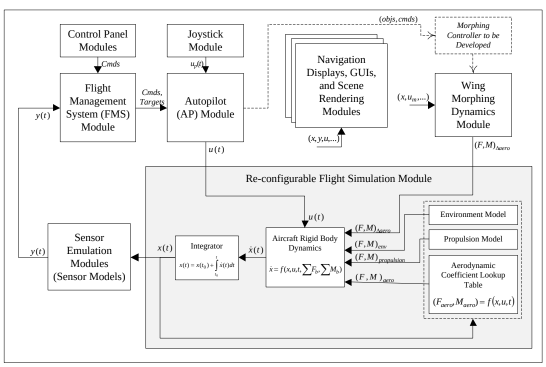

Figure 16. Simulation Architecture and Requirements

Inviscid analysis using steady-state vortex-panel method was utilized to compute Cp distribution and CL per unit section, with induced drag from finite-wing theory using trailing edge vortices. Viscous skin friction drag and separation drag is not currently being evaluated, but could be added as follow-on work. This simulation system evaluates only steady solutions (non-steady vortex-panel additions could be investigated as follow-on work). The simulation model is given by

$$\frac{d}{dt}\mathbf{P}_e = \left(\widetilde{\mathbf{\Omega}}_{Earth_e}\mathbf{P}_e\right) + \mathbf{R}_{b2e}\mathbf{V}_b$$
$$\frac{d}{dt}\mathbf{V}_b = -(\boldsymbol{\omega}_b \times \mathbf{v}_b) - \left(\mathbf{R}_{e2b}\mathbf{\Omega}^2_{Earth_e} + \mathbf{R}_{e2b}\mathbf{\Omega}_{Earth_e}\mathbf{R}_{b2e}\boldsymbol{\omega}_b\right) + \mathbf{R}_{e2b}\mathbf{g}_e + \frac{1}{m}\mathbf{F}_B$$
$$\frac{d}{dt}\mathbf{q} = -\frac{1}{2}\tilde{\mathbf{q}}\mathbf{q}$$
$$\frac{d}{dt}\boldsymbol{\omega}_b = -\mathbf{J}^{-1}\tilde{\boldsymbol{\omega}}_b\mathbf{J} + \mathbf{J}^{-1}\mathbf{T}_b$$

where body forces and moments are evaluated from the vortex-panel code that computes the difference in forces and torques between the unmodified wing (F_{umw}, T_{umw}) and morphed wing $F_{mw}, T_{mw})$ as follows.

$$\mathbf{F}_b \approx \mathbf{F}_{areo\ b} + \mathbf{M}_{ac2b}(\mathbf{F}_{mw} - \mathbf{F}_{umw})$$

$$\mathbf{T}_b \approx \mathbf{T}_{areo\ b} + \mathbf{M}_{ac2b}(\mathbf{T}_{mw} - \mathbf{T}_{umw})$$

The forces and moments are calculated through a vortex-panel code which calculates

$$\mathbf{F}_{ac} = \sum_{i=1}^{N}\left(P_\infty + \left(1 - \frac{\gamma_i^2}{U_\infty^2}\right)\frac{1}{2}\rho_\infty U_\infty^2\right)\Delta s_i\ \hat{n}_i$$

$$\mathbf{T}_{ac} = \sum_{i=1}^{N}\left((P_i - P_{cg}) \times \mathbf{F}_{i_{ac}}\right)$$

Where $\psi(s)$ is the stream function, $\gamma_i(s)$ is the surface velocities, evaluated as

$$\begin{bmatrix} K_{11} & K_{12} & \ldots & K_{1N} & 1 \\ K_{21} & K_{22} & & K_{2N} & 1 \\ \vdots & & \ddots & & \vdots \\ K_{N1} & K_{N2} & \ldots & K_{NN} & 1 \\ 1 & 0.. & ..0 & 1 & 0 \end{bmatrix}_{(N+1\times N+1)} \begin{bmatrix} \gamma_1 \\ \gamma_2 \\ \vdots \\ \gamma_N \\ \tilde{\psi} \end{bmatrix}_{(N+1)} = \begin{bmatrix} y_1 U_\infty cos\alpha - x_1 U_\infty sin\alpha \\ y_2 U_\infty cos\alpha - x_2 U_\infty sin\alpha \\ \vdots \\ y_N U_\infty cos\alpha - x_N U_\infty sin\alpha \\ 0 \end{bmatrix}_{(N+1)}$$

Additional details of the model are given in the attached report (Ippolito, 2013). The cross sectional geometry of the Swift UAS aircraft was generated by taking 2D cross sectional slices of the aircraft's outer mold line. A visual-basic script program was developed in Solidworks to automate the process of extracting cross-sectional geometries.

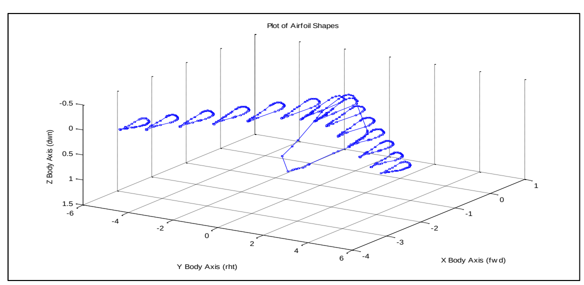

Figure 17. Swift UAS Wing Sections

The class structure and update sequence for the simulation is shown in Figure 18.

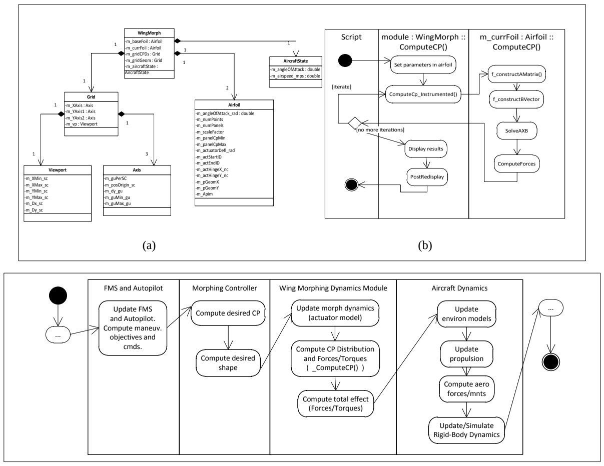

Figure 18. Class Structure and Activity Diagram for Simulation Update

The primary functions in the vortex-panel algorithm were ported and optimized for real-time computation to an NVIDIA Quadro FX 3700M GPU using the CUDA library. The resulting evaluation times are shown in Table 1 below, with the final implementation resulting in a 7 times performance improvement after this initial effort. A dedicated optimization effort would be expected to yield significant additional improvements in run-time performance. Details of the optimization and implementation are included in the attached report (Ippolito, 2013), and a screenshot of the final Reflection simulation is shown in Figure 19.

Table 1. Acceleration of Vortex-Panel Simulation using NVIDIA GPU/CUDA Optimizations

Function (time in sec)	Original	Opt A	Opt B	Opt C	Opt D
(top)	1748.5	657.1	619.5	617.6	242.1
|ComputeCP	1748.5	657.1	619.5	617.6	242.1
|+ConstructA	63.0	40.5	18.9	15.7	15.9
|+ConstructB	0.0	0.0	0.0	0.0	0.0
|+SolveAXB	1673.1	616.5	600.6	601.9	226.2
|+ComputeGamma	12.4	0.0	0.0	0.0	0.0
Total	1748.5	657.1	619.5	617.6	242.1
Improvement (x original)		2.7	2.8	2.8	7.2

Figure 19. Coupled 6-DOF Flight Dynamics with Vortex-Panel Simulation Environment

Accomplishments

All the tasks lists above were completed, including the following.

- Completed literature survey.
- Completed initial design study, requirements, and optimization for a full-scale PAWS prototype (Barrett-Gonzales, 2013).
- Completed construction of several full-scale PAWS prototypes (Barrett-Gonzales, 2013).
- Completed an initial 2D study of wing shape morphing that involved modeling, optimization and control. Developed a prototype wing morphing actuation test section on a small-scale UAV. Completed a flight readiness review but did not have time to conduct a flight test. Submitted paper to the 2012 AIAA Infotech @ Aerospace conference (Gupta and Ippolito, 2012).
- Completed creation of a simulation environment that can be integrated into NASA's hardware in the loop simulation facility (Ippolito, 2013).
- Completed derivation of a simulation model of the morphing wing vehicle utilizing a vortex panel solver that integrates into the vehicle's flight dynamics model. See the attached report draft (Ippolito, 2013).
- Conducted a study to investigate parallelization of the simulation model to increase run-time performance. Parallelized and ported model to the NVIDIA CUDA GPU environment (Ippolito, 2013).
- Created a proposed distributed wing morphing control system architecture. Completed initial

formulation of the online trajectory optimization approach (Ippolito, 2013).

Next Steps

This project shown feasibility in the concept of utilizing a morphing wing actuation for primary flight control, developed morphing prototypes on both a large unmanned glider and small unmanned UAS, developed mathematical models and GPU-accelerated vortex-panel real-time simulations, and demonstrated control feasibility and efficacy on a small-scale UAS model.

Current TRL: 4

Applicable NASA Programs/Projects

This research is applicable to NASA ARMD projects investigating drag reduction, structural aeroelastic control, lightweight materials, and adaptive and flexible wing structures. The PAHS actuation concept is a viable alternative to techniques for shape morphing such as SMA and piezoelectrics. The model and optimization analysis provides techniques and approaches that can be applied to related NASA ARMD efforts.

Publications and Patent Applications

The KU team is currently drafting patent applications for the PAWS mechanism, which are in the process of submission.

(Gupta and Ippolito, 2012) V. Gupta, C. Ippolito. "Use of Discretization Approach in Autonomous Control of an Active Extrados/Intrados Camber Morphing Wing" 2012 Infotech@Aerospace, Garden Grove, CA, USA, June 2012.

(Ippolito 2013) C. Ippolito, "Modeling and Simulation of a Variable Geometry Morphing Wing Aircraft". To be submitted to AIAA Modeling and Simulation conference 2013.

(Barrett-Gonzalez, 2013) Pressure Adaptive Wing Surface (PAWS) Flight Control and Fuel Efficiency Enhancement Research, Final Report

Awards & Honors related to Seedling Project

- Best student paper award, AIAA Infotech@Aerospace (Gupta and Ippolito, 2012)
- Vishesh Gupta, Semi-Finalist, 2012 Intel Science Talent Search (STS) competition